USAMP Low-Cost Magnesium Sheet Component Development and Demonstration Project

2019 DOE Merit Review Presentation

Presenter and PI :

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FCA US LLC

United States Automotive Materials Partnership

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Project ID #mat127

Overview

Timeline

- **Start:** October 1, 2016
- **End:** March 31, 2020
- **Percent complete:** ~65% complete

Budget

Total project funding available

DOE (70%):	$5,651,258
Contractor (30%):	$2,421,968

Funding received in FY18

DOE Share:	$2,081,496
Contractor share:	$892,070

Funding planned for FY19

DOE share:	$3,049,740
Contractor share:	$1,307,031

Partners

Primary recipient – USAMP LLC – FCA US, Ford, GM

Industry subrecipients

- AET Integration, Inc.
- Fuchs Lubricants
- Henkel Corporation
- Quaker Chemical Corporation
- Vehma International of America
- Xtalic Corporation

University subrecipients

- The Ohio State University (OSU)
- University of Florida (UF)
- University of Michigan (UM)
- University of Illinios at Urbana-Champaign (UIUC)
- University of Pennsylvania (UPenn)

LightMAT national laboratory participants

- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory

Vendors with substantial technical involvement

- Camanoe Associates
- POSCO

Barriers

- High cost of Mg sheet material, and challenges in producing automotive components with it, prevents widespread use in automotive applications.
- Lack of adequate predictive tools to enable the low cost manufacturing of lightweight Mg sheet components

Targets

- Overall – 25% vehicle glider mass reduction @ less then $5/lb saved (FOA specific – Mg sheet components at no more than $2.50/lb saved) based on 2017 U.S. DRIVE MTT Roadmap Report

Relevance

Overall objective

- Demonstrate the feasibility of producing Mg sheet components to achieve a component cost increase over conventional steel stamped components of no more than $2.50/lb saved.

Objectives (March 2018 to March 2019)

- Validate Integrated Computational Materials Engineering (ICME) predictions for formability and mechanical properties
- Optimize effective, low cost pretreatments/coatings and lubricants
- Quantify suitable joining processes
- Perform technical cost evaluation of the final alloy and processes
- Produce, evaluate and demonstrate large automotive exemplar components

Impact on Barrier(s)

- Mg sheet has the potential to reduce mass of automotive components by up to 65% compared to steel (55% projected for this project) and this project is specifically aimed to reduce cost and manufacturing obstacles preventing widespread use of Mg sheet.
- Demonstrating the feasibility of producing Mg sheet components at the target cost should enable increased usage in automotive applications
- Improved modeling capabilities of Mg alloys from raw ingot through fully formed and painted automotive components will be developed

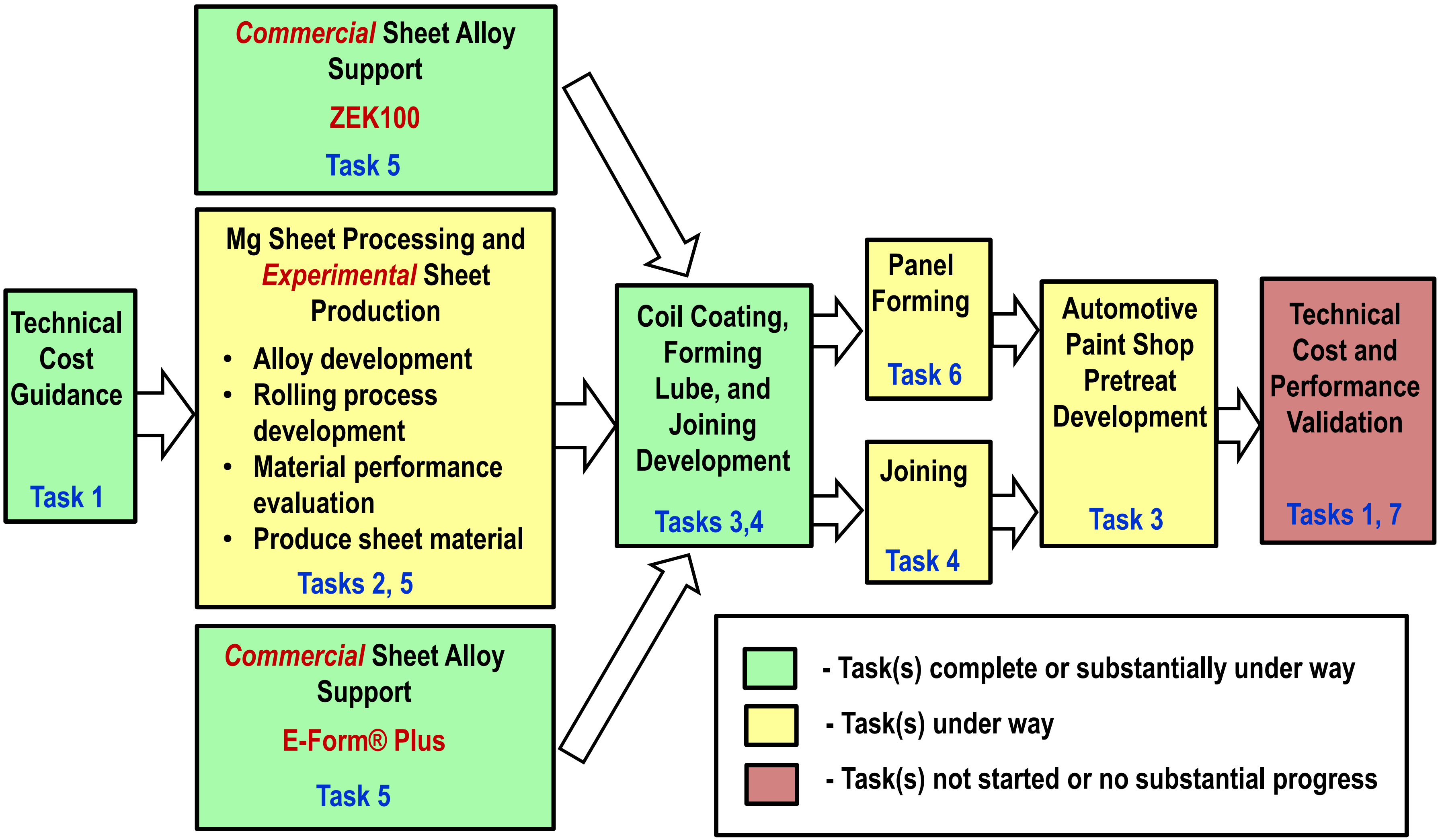
Approach / Milestones

- The program received a six month no-cost extension for BP1 due to delays in negotiating contracts with subrecipients. The table below reflects that extension.

BP	Milestone Number	Milestone Type	Task	Description	Due Date	Date Complete	Status
1	1	Go/No Go	**Task 0:** Project Management/Contracting	100% of POs issued to subs	3/30/2018	9/22/2017	**Complete**
	2	Technical	**Task 1:** Technical Cost Guidance	Baseline cost model for Mg sheet complete	3/30/2018	12/22/2017	**Complete**
	3	Technical	**Task 2:** Alloy and Sheet Processing Development	New Mg alloy sheet composition(s) identified	3/30/2018	11/3/2017	**Complete**
2	4	Technical	**Task 2:** Alloy and Sheet Processing Development	Constitutive model for textured Mg-alloy completed and ideal texture suggested	3/30/2019	N/A	50%*
	5	Technical	**Task 2:** Alloy and Sheet Processing Development	Forming analysis completed on medium sheet	3/30/2019	N/A	50%*
	6	Technical	**Task 3:** Sheet Coatings and Lubricant Evaluation and Development	Forming lubricant composition identified	3/30/2019	1/17/2019	Complete
	7	Go/No Go	**Task 5:** Mg-alloy Sheet Production	Manufacture and deliver experimental medium width sheets	3/30/2019	11/5/2019	Complete
3	8	Technical	**Task 3:** Sheet Coatings and Lubricant Evaluation and Development	Evaluation of corrosion protection coating completed	3/20/2020	N/A	40%
	9	Technical	**Task 5:** Mg-alloy Sheet Production	Delivery of wide sheet	3/20/2020	N/A	100%
	10	Technical	**Task 6:** Mg-alloy Large Body Component Production	Mg-alloy panels formed to specifications	3/20/2020	N/A	15%
	11	Technical	**Task 7:** Component(s) Demonstration	Final delivery and performance evaluation completed	3/20/2020	N/A	5%

Note: * = Milestone is expected to be achieved in BP3.

Approach


Commercial Sheet Alloy Support
ZEK100
Task 5
Technical Cost Guidance
Task 1
Mg Sheet Processing and Experimental Sheet Production
• Alloy development
• Rolling process development
• Material performance evaluation
• Produce sheet material
Tasks 2, 5
Commercial Sheet Alloy Support
E-Form® Plus
Task 5
Coil Coating, Forming Lube, and Joining Development
Tasks 3,4
Panel Forming
Task 6
Joining
Task 4
Automotive Paint Shop Pretreat Development
Task 3
Technical Cost and Performance Validation
Tasks 1, 7
- Task(s) complete or substantially under way
- Task(s) under way
- Task(s) not started or no substantial progress

Approach

- Establish a benchmark component cost and weight baseline
- Identify and quantify key cost drivers and obstacles associated with current Mg sheet material and benchmark automotive component development and manufacturing process
- Research, develop, test, and evaluate at least one new, low cost Mg alloy and commensurate processing configuration suitable for rolling thin, automotive appearance grade sheet, and forming large, challenging automotive panels.
- Leverage ICME methods coupled with experimental studies and data tools to define improved alloy chemistry(ies) and thermo-mechanical process development to achieve the following:
  - Improved formability/reduced rolling and forming temperatures
  - Mechanical properties sufficient to enable weight reduction opportunities comparable to those of today's Mg sheet materials for the selected automotive components
- Produce/obtain material test samples (both experimental and commercial) to validate ICME predictions for formability and primary and secondary mechanical properties compared to baseline ZEK100 material.
- Evaluate and develop effective, low cost pretreatments/coatings, forming lubricants and paint shop coatings
- Evaluate suitable joining processes
- Produce large size sheets for forming automotive components
- Produce and evaluate large automotive components

Approach

ICME Process and Validation

Experimental

Multi-scale Material Testing

USAMP Experimental Alloys

E-Form Plus

Modeling

Atomistic

Crystal Plasticity

Phenomenological Model

Texture Evolution

Forming Limit Diagram

Predictive

Retune Models

ICME Model Not Validated

Validation

Forming Tests and Forming Simulation – Cross Form Stamping Die

ICME Model Validated

Demonstration

Door simulation and Stamping

Technical Accomplishments

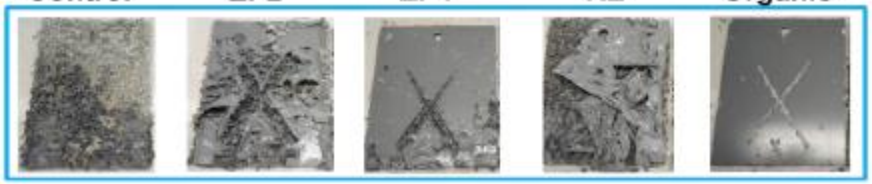
Previous Accomplishments

Identified and quantified major Mg benchmark automotive door panel cost drivers for current process and highlighted sheet metal cost as a key driver for the door inner panel

Selected first experimental alloy composition Mg-3Al-1Sn-0.3Zn-0.4Mn (ATMZ3100) and cast ingot

Evaluated potential coil applied pretreatments, lubricants, and paint shop pretreatment chemistries to work with commercially available ZEK100

- Created a new pretreatment using a zincation process for the application of Nano-Aluminum coating – Xtalic
- Screened potential lubricants to work from RT to 250°C – Fuchs and Quaker



Scribe creep comparisons of paint shop pretreatment on ZEK100 after 168Hrs ASTM B117 salt spray shows organic pretreatment significantly reduced corrosion

Used CAE tools to evaluate structural performance of 2013 Ford Fusion Door inner and outer panels based on ZEK100 material properties

- Identified 55% mass reduction from door inner and outer

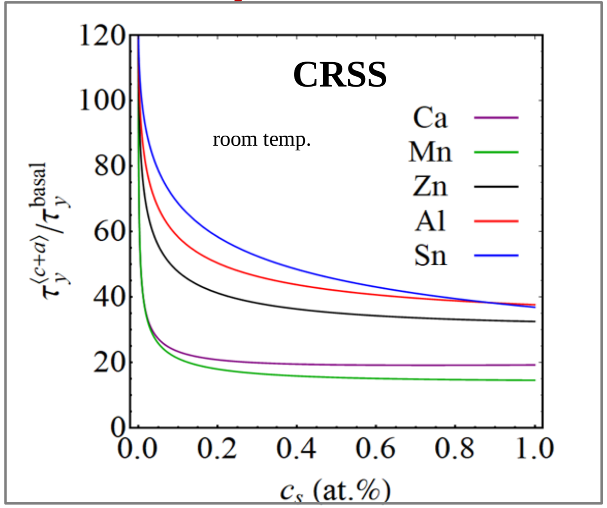
Technical Accomplishments

ICME Development – Atomistics and Thermodynamics

Atomistics/Density Functional Theory (DFT) (UIUC):

- Calculate solution strengthening of non-basal deformation modes to reduce plastic anisotropy (activate more slip systems) to improve plasticity

✓ Large solutes (Ca, Mn) show greatest core-solute interaction and are most effective for reducing plastic anisotropy (inputs from OSU, UM, UF)



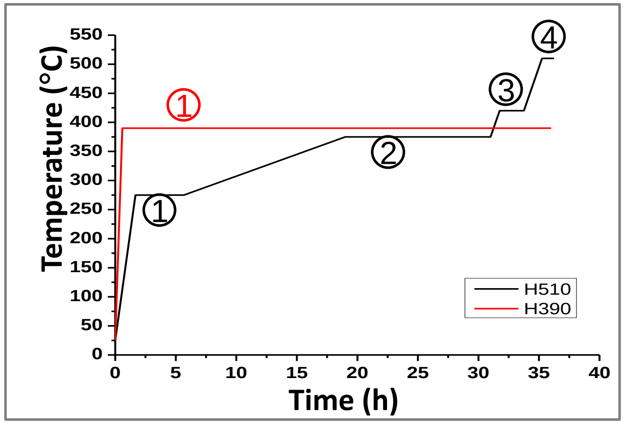
Critical Resolved Shear Stress (CRSS) shows Ca, Mn are most effective at reducing plastic anisotropy

Computational thermodynamics (OSU):

- Define usable novel chemistry boundaries from input of influence of elemental additions on strength, texture (UM), and enhancing non-basal slip for enhanced plasticity (UIUC)

✓ Designed Alloy 2 (Mg-2Zn-0.3Ca-0.4Mn-0.2Ce)

✓ Defined multi-stage homogenization and rolling schedule to maximize use of alloying additions



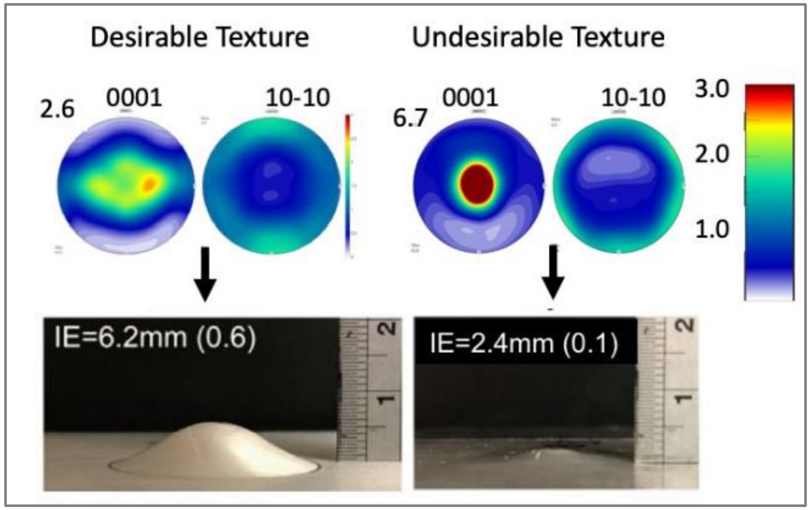
Multi-stage homogenization schedule for Alloy 2 based on CALPHAD modeling

Technical Accomplishments

ICME Development – Texture Development

Alloy effects on texture evolution (UM):

- Optimize chemistry & thermomechanical processing (input for Alloy 3)
- Quantify texture evolution mechanisms (deformation vs recrystallization)
- ✓ Identified desirable texture features for enhancing formability
- ✓ Developed TMP procedures and detailed EBSD data (UPenn)



Left side shows desirable texture and acceptable dome height for E-Form Plus, while and the right side shows Alloy 1 with strong basal and poor dome height

Solute effects and texture development (UF):

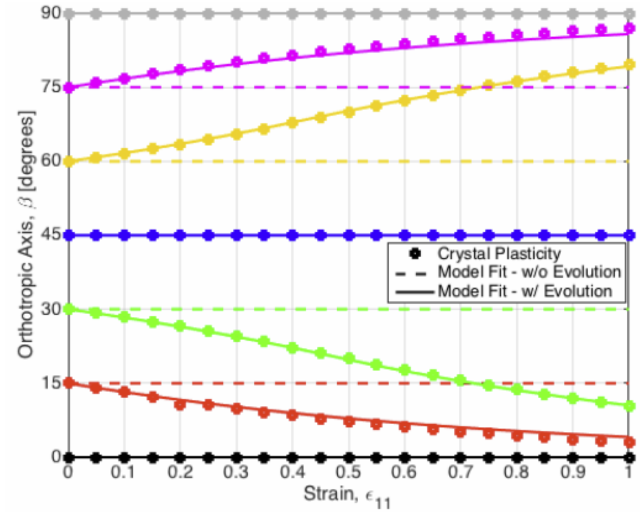
- Develop solute strengthening models
- Validate UIUC DFT calculations
- Provide input for thermodynamics and recrystallization/texture studies
- ✓ Evaluated Alloys 1 and 2, and fabricated binary and ternary model alloys for microstructural characterization and dynamic behavior (input for Alloy 3)

Technical Accomplishments - ICME

ICME Development – Phenomenological Model

Formability modeling (UPenn and Inaltech):

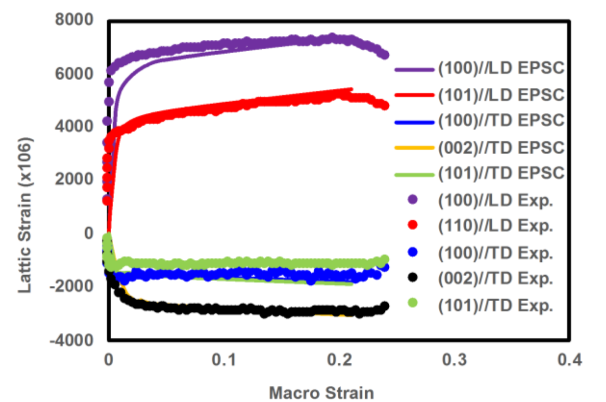
- Develop polycrystal model that accounts for evolution of slip and twinning in finite element calculations of door stampings
- Input from:
  - ✓ EBSD data at interrupted strains (UM)
  - ✓ Ratios of critical yield stresses on different slip systems (UIUC)
  - ✓ Array of experiments (PNNL)



Aluminum baseline shows how strain rotates the orthotropic axis

Inputs for modeling (PNNL):

- Understand impact of specific solutes (UF) and texture on lattice strain evolution
- Validate UIUC DFT calculations with EBSD
- Quantify slip-system-dependent parameters for plasticity models (UPenn)
- ✓ In-situ tensile testing (inside HEXRD)
- ✓ Elevated temperature tensile and LDH



High energy x-ray diffraction of ZEK100 used to calibrate the crystal plasticity model

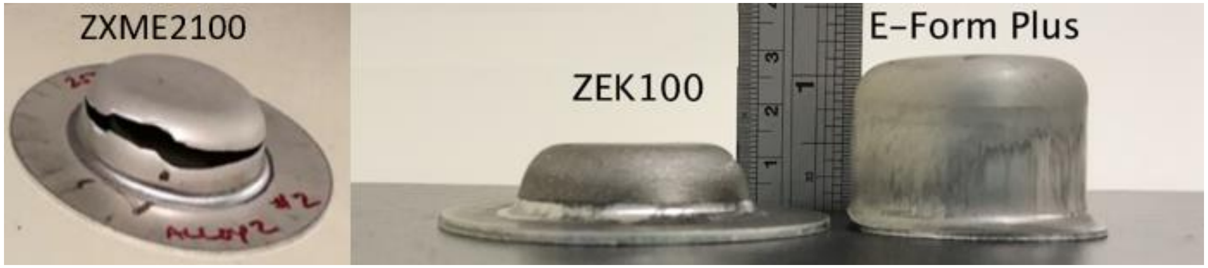
Technical Accomplishments

ICME and Alloy Development

ICME Inputs	Alloy Number	Status
Thermodynamics and Kinetics	**Alloy 1** (ATMZ3100) Mg-3Al-1Sn-0.4Mn-0.3Zn	• Phase fractions accurate, BUT • **Appropriate texture (formability) not realized** • **Identified gap between modeled and desired texture**
+ Atomistics via DFT **(This Project)**	**Alloy 2** (in progress) (ZXME2100) Mg-2Zn-0.5Ca-0.4Mn-0.2Ce	• Highest combined strength and elongation ever achieved! BUT • **Formability not realized (still a texture issue)** • Continuing optimization of chemistry and rolling • ORNL "shear" rolling mill to be used as an additional approach to drive improved texture
+ Recrystallization texture models **(This Project)**	**Alloy 3** (in progress) Mg-Ca-Zn	• Chemistry and processing refinement by model improvements and experimental information (This Project) • ORNL "shear" rolling mill to be used

Erichsen cup test was used to evaluate formability of experimental and commercial alloys

- E-Form Plus was the only alloy to form a full cup at 250°C
- **Made key decision to proceed with E-Form Plus to form demonstration door panels**



Erichsen cup testing of ZXME2100 (left), ZEK100 (center) and E-Form Plus (right) performed at 250°C shows only E-Form plus was capable for forming the full cup without fracture.

Technical Accomplishments

Coil Applied Coating Development – Henkel and Xtalic

Henkel:

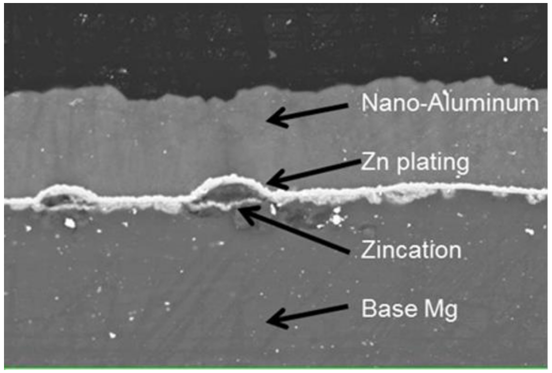
Developed and optimized pretreatment (Process D) to work with commercially available E-Form Plus Alloy

- Passed 48 hours ASTM D2247 humidity test
- Improved adhesive lap shear strength from 5.6 MPa to 11.50 MPa
- Bend test results yielded no reduction in performance
- Feasible for resistance spot welding

Humidity Test of bare (left) and process D pretreated (right) E-Form Plus sheet shows pretreatment successfully prevented oxidation and corrosion.

Xtalic:

- Adapted zincation and zinc plating process to current commercially available state of the art Mg sheet alloy E-Form Plus
- **Key decision made to proceed with zinc coating only** without nanostructured aluminum electroplating due to zinc's low cost and current manufacturing feasibility on steel sheet applications.
- Dome height testing showed no issues with zinc coating but did show significant cracking of the aluminum coating.



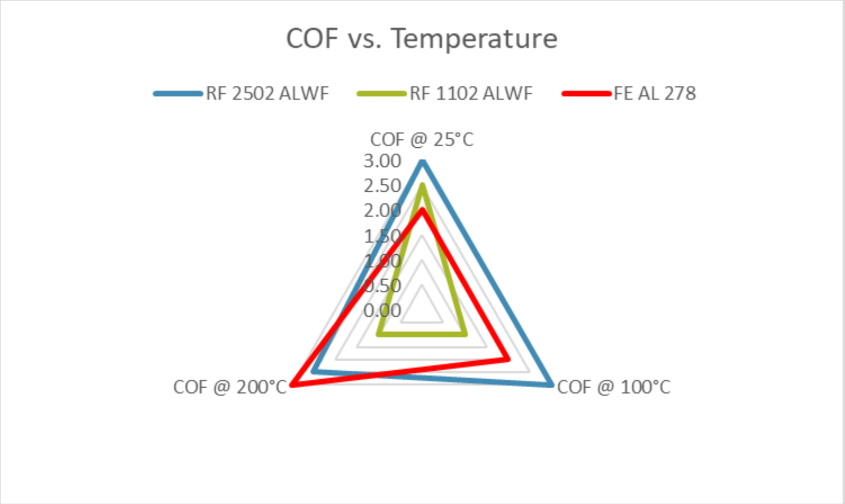
SEM micrograph of the plated layers on ZEK100.

Technical Accomplishments

Warm Forming Lubricant Development – Fuchs and Quaker

Fuchs

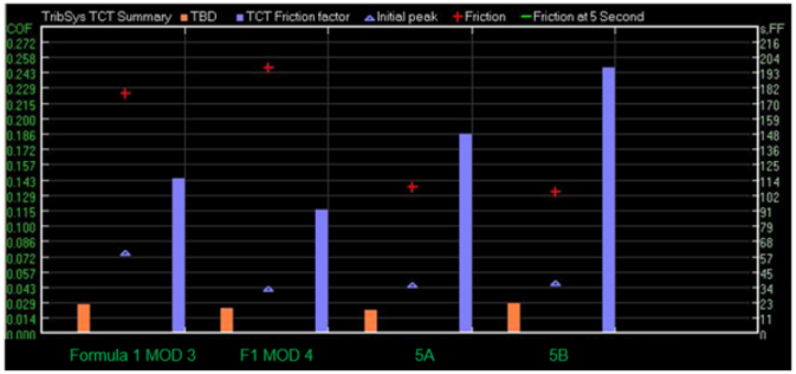
- Evaluated potential lubricants to work with E-Form Plus from RT to 250°C
- **RF 2502 ALWF is the overall best performing FUCHS lubricant for use in forming E-Form Plus**



Coefficient of friction rankings on E-Form Plus. Higher the ranking number, the lower the COF under elevated temperature

Quaker

- Evaluated potential lubricant formulas to work with E-Form Plus at four temperatures between 100° and 250°C
- **Formula 5B is the overall best performing Quaker lubricant for use in forming E-Form Plus**



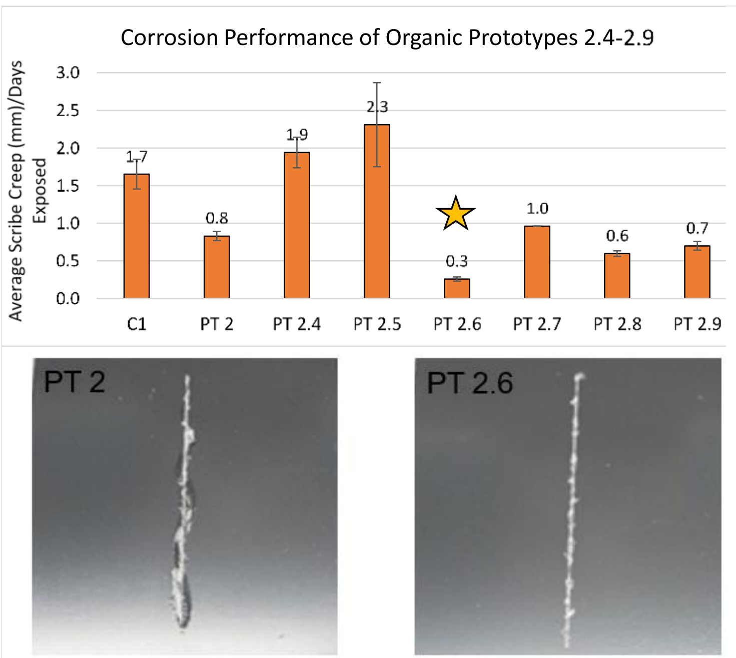
Sample	Initial Peak		Friction		Time to Breakdown		TCT Friction Factor	
	Ave.	Stdev.	Ave.	Stdev.	Ave.	Stdev.	Higher is better	Stdev.
Formula 1 MOD 3	0.078	0.022	0.225	0.052	22.40	7.117	115	49.4
Formula 1 MOD 4	0.045	0.036	0.249	0.047	19.15	2.595	92	29.0
Formula 5A	0.048	0.039	0.137	0.005	17.61	1.354	148	50.1
Formula 5B	0.050	0.031	0.133	0.004	22.89	2.239	197	56.3

Twist compression analysis of 4 screened lubricants at 250°C on Henkel pretreated (C) E-Form Plus at 3,000 psi

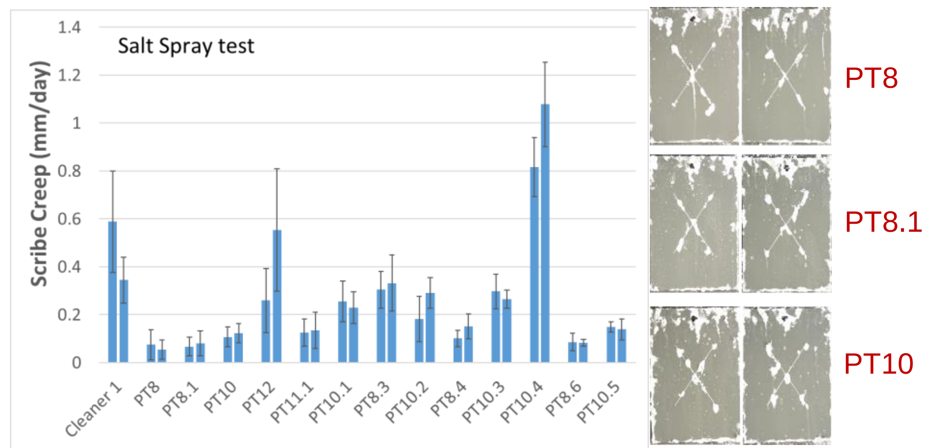
Technical Accomplishments

Paint Shop Applied Coating Development - PPG

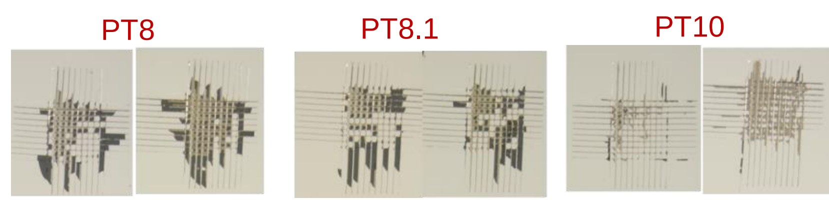
- Evaluated potential paint shop pretreatment chemistries to work with E-Form Plus
  - **Established Cleaner 2 as an important pretreatment step for protection of E-Form Plus**
  - Prototype organic PT 2.6 shows the best corrosion performance on Bare EFP
  - Novel pretreatment chemistry PT8 shows the best corrosion performance on Henkel's coil coated panels; however, wet adhesion requires further development.



Scribe creep comparisons of organic pretreatments on bare E-Form Plus show PT 2.6 has best performance.



Scribe creep comparisons of novel pretreatments on E-Form Plus with Henkel's coil coating process C.



Wet adhesion comparisons of novel pretreatments on E-Form Plus with Henkel's coil coating process C

USAMP

Technical Accomplishments

Mg-Alloy Large Body Component Production

- Defined methodology for warm forming simulation of door inner and outer panels
  - LS-Dyna was selected as the software to be used for warm-forming simulation
  - LSTC code developers updated MAT233 material card with 3D table to define hardening behavior for temperature and strain rate.
  - A baseline simulation will be performed using current state of the art MAT36 material card and compared to newly improved simulation using modified MAT233 card

3D table that defines hardening behavior

Card 2	1	2	3	4	5	6	7	8
Variable	A	C11	C22	C33	$\boxed{\text{LCID}}$	E0	K	P3
Type	F	F	F	F	I	F	F	F

Table ID vs. temperature

```
*DEFINE_TABLE_3D
$     T3BID        SFA       OFFA
      10000
$          TEMPERATURE   TABLE_ID
                273.15      10100
                773.15      10200
                823.15      10300
                873.15      10400
                923.15      10500
                973.15      10600
               1023.15      10700
               1073.15      10800
               1123.15      10900
               1173.15      11000
```

LCID vs. strain rate

```
*DEFINE_TABLE_2D_TITLE
T=273.15
$      TBID        SFA       OFFA
      10100
$       STRAIN_RATE   CURVE_ID
            0.01000      10101
            0.05000      10102
            0.10000      10103
            0.50000      10104
            1.00000      10105
            5.00000      10106
           10.00000      10107
```

Effective stress vs. equivalent plastic strain

```
*DEFINE_CURVE_TITLE
T=273.15 strain_rate=0.010
$     LCID       SDIR        SFA        SFO
     10101                              1.20
$ EFF_PLASTIC_STRAIN          YIELD_STRESS
            0.0000               131.570
            0.0025               157.967
            0.0050               166.473
            0.0075               172.669
            0.0100               177.721
            0.0150               185.913
            0.0200               192.593
            0.0250               198.335
            0.0300               203.425
            0.0350               208.031
            0.0400               212.258
            0.0500               219.850
            0.0600               226.581
            0.0700               232.671
            0.0800               238.260
```

3D table added to MAT.233 material card to define hardening behavior allows for input of many temperature and strain rate values to define multiple curves

USAMP Responses to Previous Years Reviewers' Comments

Comments from the 2018 Annual Merit Review	Response
It did not seem like the task "Alloy and sheet processing development—New Mg alloy sheet composition(s) identified" is "complete."	E-Form Plus has been selected as the alloy to warm form door panels thereby completing the task of identifying the alloy sheet composition.
The reviewer inquired if adding process steps (coating) to these alloys is going to get us anywhere near cost targets. The reviewer expressed having difficulty gleaning this information or the cost comparison with ATMZ3100	The proposed addition of a coil applied pretreatment such as Henkel's process D or Xtalic's zinc coating will reduced cost by changing the magnesium sheet production process to be closer to that of a steel production process which uses a pretreatment coating in favor of the more expensive alodine dip/powder coat process currently used with magnesium. The material cost is the major cost driver on the door inner panel and this project will reduce that cost by selecting an alloy composition that can be manufactured using the less expensive continuous casted process. The technical cost model will be updated in budget period 3 with the selected alloy and coatings.
The reviewer remarked that touting ICME as a critical component seems to have fallen largely by the wayside with the abrupt selection of ATMZ3100 as the material of choice following a literature search and a few calculations.	ICME was not used for ATMZ3100 due to the timing limitations of developing the model and alloy composition while still maintaining enough time to cast, roll, characterize and scale up the alloy to large sheet. ICME is being utilized for our third experimental Mg Ca Zn based alloy. It was composed in a University setting, building the database for Mg Ca Zn interactions and it was validated using solid-solution strengthening models developed by University Illinios at Urbana-Champaign. .

Collaboration and Coordination

- Broad participation of domestic OEMs, suppliers and universities (over 15 in total)
- Project executed at task level (7 task teams) and coordinated by a USAMP leadership team

U.S. Partner Organizations

USAMP Leadership Team

FIAT CHRYSLER AUTOMOBILES

Randy Gerken, *Principal Investigator*
Leland Decker
Aslam Adam
Dajun Zhou
Jugraj Singh

Bita Ghaffari
Mei Li

Anil Sachdev
Lou Hector
Arianna Morales

MANAGE INNOVATION SUSTAINABLY
M-TECH INTERNATIONAL LLC

Manish Mehta, Technical Project Manager
John Carter

Organization	Responsibility
Industry subrecipients (7)	
AET Integration, Inc.	– Joining process evaluation
Fuchs Lubricants Co	– Development of forming lubricants for temps up to 250°C
Henkel Corporation	– Development of coil applied anti-corrosion treatments
PPG Industries	– Development of paint shop applied anti-corrosion coatings for Mg components
Quaker Chemical Corporation	– Development of forming lubricants for temps up to 250°C
Vehma International of America	– Production (stamping) of large Mg components
Xtalic Corporation	– Develop coil applied aluminum plating for Mg corrosion protection
University subrecipients (5)	
The Ohio State University	– Mg alloy design, evaluation, and validation.
University of Florida	– Provide Mg thermodynamic and kinetic data for alloy development
University of Illinois at Urbana-Champaign	– Atomistic modeling for Mg crystal plasticity model development
University of Michigan	– Precipitate evolution and dynamic recrystallization characterization and modeling
University of Pennsylvania	– Develop constitutive model for textured Mg-alloy sheets, FE material user subroutine, drawing and formability simulations, and determine forming limits
LightMAT National laboratory subrecipients – (2)	
Oak Ridge National Laboratories (ORNL)	– Development of optimized Mg sheet rolling process parameters and production of Mg strips for material model calibration and validation
Pacific Northwest National Laboratories (PNNL)	– Mg forming model development, data management, and mechanical properties characterization
Vendors (2)	
Camanoe Associates	– Technical cost analysis and guidance
POSCO	– Production of large and medium width Mg sheet

Remaining Challenges and Barriers

- Coatings, forming lubricants, and joining process interactions must be finalized and fully validated on E-Form Plus.
- E-Form Plus must be characterized for mechanical properties to support forming simulation and structural design before producing door panels
- Structural performance and appearance must be physically validated from door panels formed from E-Form Plus
- Technical cost evaluations must be conducted once E-Form Plus and its coating, forming lubes, joining processes and forming processes are finalize for comparison to a) existing steel door panels, and b) current Mg sheet processes
- ICME modeling must be further developed and continued to be integrated into the third experimental alloy to develop a novel alloy composition methodology capable of warm forming door panels

Proposed Future Research

*** Any proposed future work is subject to change based on funding levels ***

- Proposed Future Work – **FY 2019**
  - Validate ICME predictions for formability and primary and secondary mechanical properties
  - Continue development of low cost coil applied pretreatments, lubricants, and coatings with E-Form Plus
  - Continue to evaluate suitable joining processes
  - Optimize performance and cost of alloy, rolling process, coatings, treatments, lubes, etc. for comparison to current commercial alloys and processes.

- Proposed Future Work – **FY 2020**
  - Produce and evaluate large automotive exemplar components
  - Demonstrate performance of Mg sheet panels

Summary

- Project leverages broad industry and academic participation:
  - 19 participants doing substantial technical work, including 3 U.S. Auto OEMS, 7 industry subrecipients, 2 vendors, 5 universities, and 2 national laboratories (via LightMAT)

- The holistic approach, with the exception of raw ingot production, includes every major step of the process from:
  - alloy chemistry and sheet rolling process development
  - new coil applied coatings and warm forming lubricants
  - warm forming and joining process development
  - paint shop pretreatment process developed to work with Mg, Al, and steel
  - final cost, weight, and performance evaluation at end of project

- Significant technical accomplishments over this period include:
  - Developed and identified two coil applied coatings and two lubricants ***(Milestone 6)*** that are effective with E-Form Plus and compatible with the warm forming process.
  - Developed solid-solution strengthening models which were used to validate twinning and slip plane modes for the third experimental alloy, Mg-Ca-Zn base composition
  - Evaluated formability of experimental and commercial alloys and selected E-Form Plus **(Milestone 3)** as the material that will be used for warm forming door panels

Acknowledgement

Acknowledgment: "This material is based upon work supported by the Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), under Award Number DE-EE0007756."

Technical Back-Up Slides

Technical Back Up

UIUC – Atomistic modelling of non-basal slip

Approach:

- Solution strengthening of non-basal deformation modes
  - DFT: dislocation cores, solute-dislocation interactions
  - DFT data → Labusch strengthening models
- Inputs: solute chemistries from OSU, UM, UF

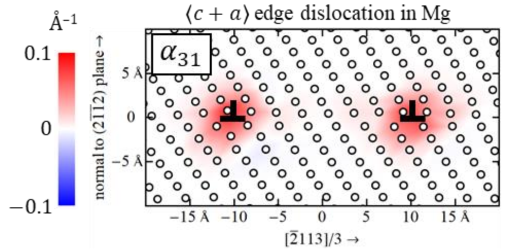
Progress:

- Optimized cores and solute interactions: $\langle c + a \rangle$ edge and screw, $(10\bar{1}1)$ twinning edge
- Strength predictions: $\langle c + a \rangle$ edge, $(10\bar{1}2)$ twinning edge
- Outputs: testing by PNNL; CP/ReX models at PNNL and UM

Plans:

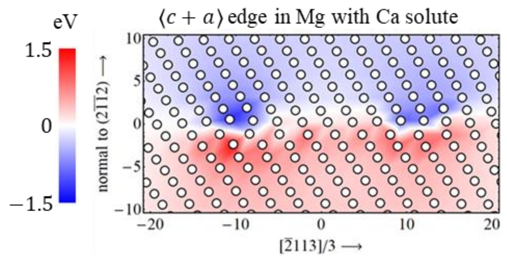
- Predict strength for $\langle c + a \rangle$ screw, $(10\bar{1}1)$ twinning edge
- Interface CRSS and phase stability calculations to predict Mg alloy chemistries with improved strength and ductility

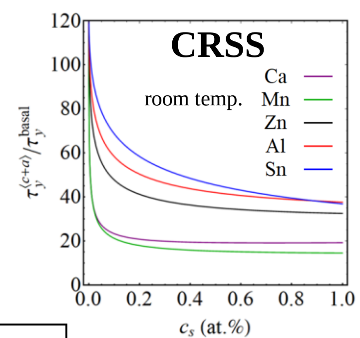
core geometries



+

solute-dislocation interactions





Predicted effect of solutes on $\langle c + a \rangle$ and twinning dislocation slip

Technical Back Up

University of Florida : Solute Effects on Texture Development

Approach:

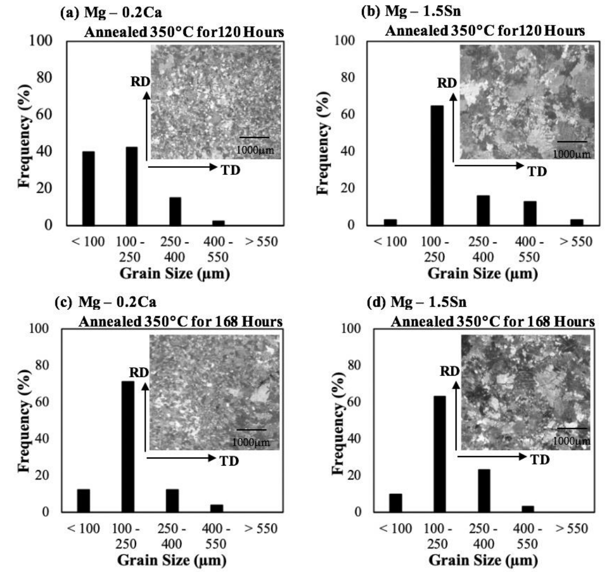
- **Solute Strengthening Model Development and DFT Experimental Validation:** Characterize the behavior of Mg-Sn and Mg-Ca alloys to produce microstructural, mechanical behavior and thermodynamic data. This data will provide an understanding of the strain rate and recrystallization behavior to provide unit level mechanistic understanding for alloy development. Input from UIUC with cast samples sent to PNNL for experimental testing.
- **Mg-Ca-Zn (Experimental Alloy 3):** Cast Mg-Ca and Mg-Ca-Zn samples for recrystallization studies at the University of Michigan

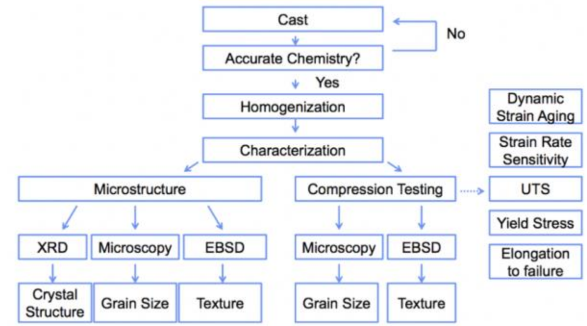
Progress:

- Provided detailed microstructural analysis on the effect of time, temperature, and cold work on grain size distribution and precipitate phase stability in Mg-Sn and and Mg-Ca alloys.
- Cast and shipped 27 homogenized and fully characterized (grain size distribution and phase stability as a function of heat treatment time and temperature.) Mg-Ca and Mg-Ca-Zn castings to the University of Michigan

Plans:

- 4 sheets of optimally cold-worked and annealed Mg-Sn and Mg-Ca will be shipped to PNNL for characterization and DFT validation
- Mechanical testing at various strain rates and temperatures to characterize dislocation-solute interactions and provide material property inputs to computational models for the Mg-Ca and Mg-Ca-Zn alloy system





Flowchart summarizing the experimental flow path.

Mg-Ca and Mg-Sn fabrication and characterization for DFT modeling validation

Mg-Ca and Mg-Ca-Zn fabrication and characterization for recrystallization and texture studies

Technical Back Up

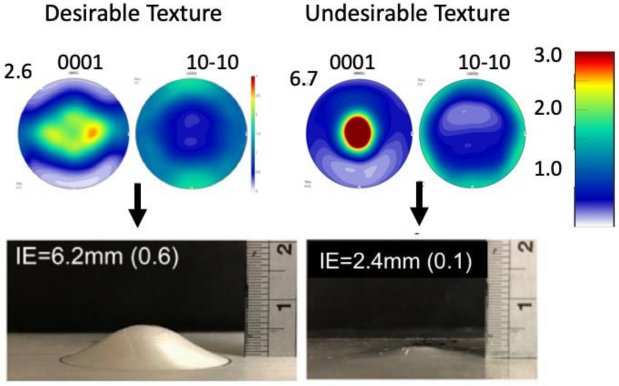
UM – Texture Evolution in Formable Mg Alloys

Approach:

- Quantify alloy effects on texture evolution (TMP + EBSD)
- Mg-Zn-Ca alloys based on U. Illinois calculations and literature; TMP based on ThermoCalc and lit

Progress:

- Identified desirable textures in formable Mg alloys
- Developed TMP procedures, received alloys (U Florida) and completed initial experiments



Plans:

- Define optimum combination of Mg-Zn-Ca and TMP recipe
- Quantify texture evolution mechanisms (deformation vs recrystallization) for future ICME

Identified desirable textures and promising alloys

Technical Back Up

The Ohio State University – Computational Alloy Design

Approach:

- Alloy and thermomechanical process (TMP) design
- Use thermodynamic and kinetic databases including DFT data (e.g., UIUC data and literature)

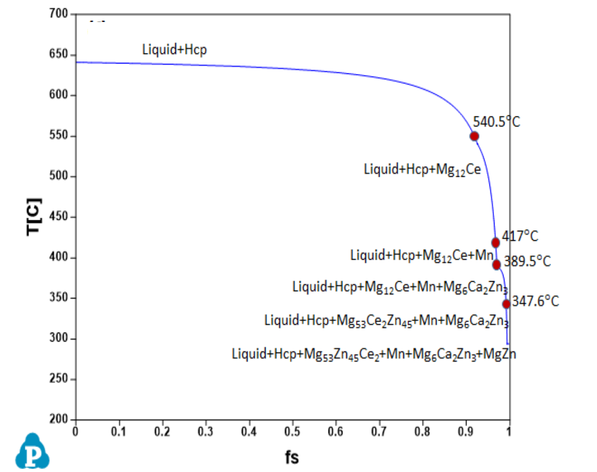
Progress:

- Alloy 2 (Mg-2Zn-0.3Ca-0.4Mn-0.2Ce)
  - Zn for solid solution strengthening
  - Ca and Ce for texture modification
  - Mn for corrosion resistance and strengthening
- Multi-stage homogenization based on CALPHAD
- UM is evaluating texture and formability of Alloy 2 sheet samples from OSU

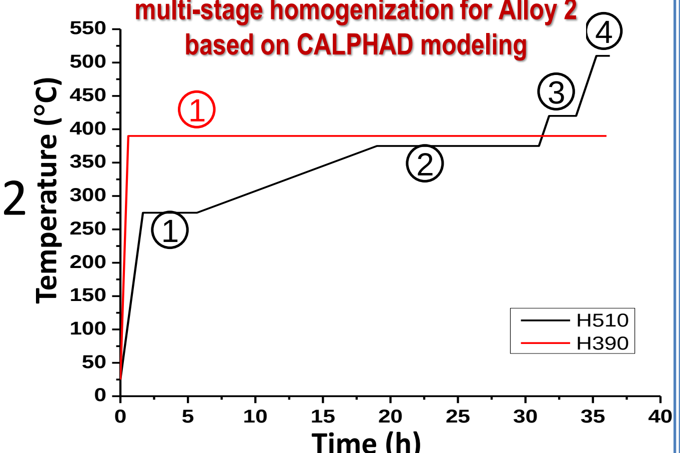
Plans:

- Optimizing Alloy 2 chemistry and TMP

CALPHAD-Scheil model of solidification path of Alloy 2



multi-stage homogenization for Alloy 2 based on CALPHAD modeling



Alloy 2 (Mg-2Zn-0.3Ca-0.4Mn-0.2Ce) and its thermomechanical process developed based on thermodynamic and kinetic modeling

Technical Back Up

University of Pennsylvania (J. L. Bassani) and Inaltech (K. Inal)

Polycrystal and Phenomenological Modeling

Approach:

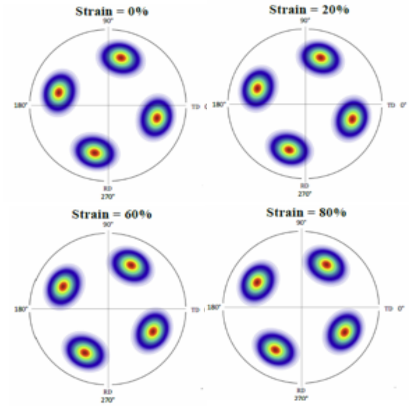
- Polycrystal modelling that accounts deformation by slip and twinning will provide input for both LS-DYNA MAT 233 (fixed material symmetry) for Magna's work and for Bassani's model that accounts for the evolution of material symmetry axes.
- Input for both models will come from tensile experiments at PNNL and EBSD data from University of Michigan as well as published data on Mg alloys.

Progress:

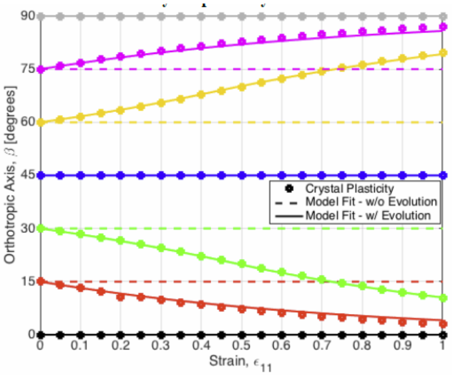
- The overall approach has been accomplished in a recent collaboration between Bassani and Inal on an aluminum alloy (see graphics). The framework for Mg alloys is in development.
- A collaboration between UPenn and PNNL has refined the PNNL experimental plan. There is an important interplay between experiments and polycrystal simulations in developing the models.

Plans:

- The models will be used to simulate forming limits and the software will be made readily available to USAMP researchers.



Evolution of pole figures for 30° off-axis tensile stressing at various strain levels for an aluminum alloy.



Orthotropic axis evolution as a function of uniaxial off-axis strain: Data generated from polycrystal simulations and calibrated using phenomenological model. C.P. Kohar, J.L. Bassani, A. Brahme, W. Muhammad, R.K. Mishra, K. Inal, Int. J. Plasticity 2018)